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Efficient Laser Light Absorption by Ion Acoustic Fluctuations

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A new efficient absorption mechanism for intense laser light in plasma resulting from an ion acoustic instability generated by a return current is described. Comparisons with experimental results are presented.

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EFFICIENT LASER LIGHT ABSORPTION BY ION ACOUSTIC FLUCTUATIONS

This Letter presents a new absorption mechanism which gives efficient absorption of intense light by a laser produced plasma. The basic idea is that in absorption, the laser energy flux is converted into an electron thermal energy flux Q flowing into the plasma. In order for charge neutrality to be maintained, there must be a return current of low velocity electrons flowing toward the laser (in the negative x direction). This return current excites ion acoustic waves, also propagating toward the laser. The laser light then experiences enhanced collisional damping on these ion density fluctuations in the underdense plasma. The absorption of the laser light then creates that very electron thermal energy flux which was required in the first place.[1,2,3] Values of Q/nmv_e^3 are small enough that a fluid model (dominated by anomalous transport) is valid. Finally, we show that a magnetized plasma should give both higher absorption and also remove some of the approximations inherent in the calculations presented here for an unmagnetized plasma.

Results of our theory seem to be in good qualitative agreement with many absorption, scattering and x-ray measurements at NRL.[4-7] It would be very difficult to explain these measurements by resonant absorption.[8] The measurements consistently show high fractional absorption (in excess of 50%) which is relatively independent of both polarization and angle of incidence.[5] In addition, NRL experiments indicate a fairly smooth critical surface for distance scales above about one micron.[7] Also light absorption by enhanced ion density fluctuations would not tend to strongly produce non thermal electrons. Energy flux is found to be carried principally by electrons at

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about two or three times the thermal speed. This also seems to be in agreement with hard x-ray measurements.[4,6] Finally, layered target experiments[4] indicate a value of Q/nmv_e^3 less than 0.2 which is also in agreement with our calculations. We now describe our calculations, and will close by giving more detailed comparisons with experimental results.

The relevant steady state fluid equations have been written out and discussed elsewhere.[1] We summarize them here as:

$$\frac{\partial}{\partial x} nT_e + neE + \frac{1}{4}\frac{e^2}{m^2\Omega^2}\frac{\partial}{\partial x}(E_i^2 + E_r^2) = C_{ve} \qquad \text{(a)}$$

$$\frac{\partial Q}{\partial x} = C_{Te} + \nu_{an}\left(\frac{E_i^2 + E_r^2}{8\pi}\right)\frac{\omega_{pe}^2}{\Omega^2} \qquad \text{(b)}$$

$$\frac{3}{2}\frac{\partial}{\partial x} nT_e^2 + \frac{3}{2}\frac{T_e}{m}\left(neE + \frac{1}{4}\frac{e^2}{m^2\Omega^2}\frac{\partial}{\partial x}[E_i^2 + E_r^2]\right) = C_{Qe} \qquad \text{(c)}$$

$$\text{(1)}$$

$$nv = \text{const.} \qquad \text{(d)}$$

$$nMv\frac{\partial v}{\partial x} + \frac{\partial}{\partial x} nT_i - neE = -C_{ve} \qquad \text{(e)}$$

$$\frac{\partial}{\partial x}\frac{3}{2} nvT_i + nT_i\frac{\partial v}{\partial x} = -C_{Te} \qquad \text{(f)}$$

where E is the ambipolar electric field. $E^2_{i(r)}$ is the intensity of the incident (reflected) laser light, Q is the electron thermal energy flux in the x direction, Ω is the laser light frequency, ν_{an} is the anomalous collision frequency, and C_{ve}, C_{Te}, C_{Qe} are quasi-linear collision terms which describe the electron momentum, thermal energy and thermal energy flux loss

due to interactions with unstable waves. In Eq. 1c, the effects of ponderomotive force have been included. All other notation is standard.

Coupled to this fluid system are equations for the incident and reflected laser light and also equations for the unstable ion acoustic waves. These are

$$c\frac{d}{dx}\left(\cos^2\theta - \frac{\omega_{pe}^2}{\Omega^2}\right)^{\frac{1}{2}} E^2_{i(r)} = -(+)\nu_{an}\frac{\omega_{pe}^2}{\Omega^2} E^2_{i(r)}, \qquad (2)$$

where θ is the angle of incidence of the laser light and

$$\frac{d}{dx}\left|\frac{e\varphi(k)}{T_e}\right|^2 = 2\left(\gamma/\left(v-(T_e/m)^{\frac{1}{2}}\right)\right)\left|\frac{e\varphi(k)}{T_e}\right|^2, \qquad (3)$$

where γ is the growth rate.[1]

The final quantities to specify are C_{ve}, C_{Te}, C_{Qe} and ν_{an}. The quantity ν_{an} depends on the component of $\underline{k}$ in the direction of $\underline{E}_i$ (for instance the y direction). Thus the angular spectrum of the ion acoustic fluctuations is needed. We make use of results of many numerical simulations of ion acoustic turbulence in two dimensions,[9] which show a cone of unstable waves out to an angle of between about 45 and 60 degrees. We use this basic result and assume a three dimensional conical spectrum uniform in angle up to 55° to the x axis and then dropping sharply to zero. Making this assumption, we find[1]

$$\nu_{an} = \Omega \frac{\omega_{pe}^2}{\Omega^2} \frac{3k_{min}}{k_{max}} \sum_{k=k_{min}}^{k_{max}} \left(\frac{k}{k_{max}}\right)^2 \quad 0.3\pi \left(\frac{\omega_{pe}}{\Omega}\right)^3 k\lambda_D \cdot$$

$$\left[\left(1 - \frac{\omega_{pe}^2}{\Omega^2}\right)^2 + 4\left(\frac{\omega_{pe}^2}{\Omega}\right)^6 k^2\lambda_D^2\right]^{-1} \left|\frac{e\varphi(k)}{T_e}\right|^2 . \tag{4}$$

where k_{min} and k_{max} are the minimum and maximum wave numbers included in the summation. In our calculations we take $k_{max} = 0.75\ k_D$ and $k_{min} = k_{max}/9$. The C's are calculated as in Ref. 1, only making the same conical approximation to the wave spectrum.

Now it is worthwhile pointing out that if a transverse magnetic field exists, as is usually the case for laser light focused on a slab,[10] the ion acoustic wave no longer propagates parallel to $\underline{Q}$, but parallel to $\underline{E}_i$.[11] Thus not only would ν_{an} increase, but also there would be no need to make any approximations concerning the angular width of the spectrum. In a future publication, we plan to discuss the problem of absorption in a magnetic field.

Equations 1 through 4 are a coupled set of equations which we solve numerically starting at $x = 0$ and integrating backwards towards the laser. As initial values, we start with parameters characteristic of the low density shelf as explained in Ref. 12, and $\sum \left|\frac{e\varphi}{T_e}\right|^2 = 10^{-5}$. At a given subcritical density, the flow velocity v, and v_{os}/v_e are determined.[12] Also $E_i^2 = E_r^2$ at $x = 0$. Choosing an electron temperature is then essentially equivalent to choosing an incident laser power. The remaining initial

parameters to be specified are T_i/T_e and Q. The parameter $Q(x = 0)$ is found by iteration so that $Q(x = -\infty) = 0$.

Results are shown in Fig. 1a-d. Figure 1a shows the spatial dependence of T_e, Q, E_i^2, E_r^2 and $\left[\sum \left|\frac{e\varphi(k)}{T_e}\right|^2\right]^{\frac{1}{2}}$ where T_e $(x = 0) = 12$ keV, $T_i(0)/T_e(0) = 1/30$, $\omega_{pe}^2(0)/\Omega^2 = 0.7$, and $\theta = 0$. Following E_i^2 back to $-\infty$, we see that the incident laser flux is 10^{15} W/cm^2, $Q(0)/nmv_e^3(0) \approx 0.1$, and the absorption efficiency is 66%. The unstable wave spectrum peaks at about $k \sim k_D/2$. The electrons which principally absorb the laser light have velocity $\sim \Omega/k \sim 3v_e$ so that an energetic tail is not expected to be substantially produced. Figure 1b shows the absorption efficiency as a function of density on the low density shelf assuming $T_e(0) = 12$ keV and $T_e(0)/T_i(0) = 30$. Figure 1c shows values of $Q(0)/nmv_e^3(0)$, $T_e(0)$ and absorption efficiency as a function of laser power where $n(0) = 0.5\ n_{cr}$ and $T_e(0)/T_i(0) = 30$. The high temperatures calculated here, of course, exist only in front of the critical surface. At higher densities, the temperature would be much lower. Figure 1d shows the absorption efficiency as a function of angle for $n(0) = 0.5\ n_{cr}\cos^2\theta$ (see Ref. 12), $T_e(0)/T_i(0) = 30$ and $T_e(0) = 12$ keV (the incident laser flux was in the vicinity of 2×10^{15} W/cm^2). The fractional absorption would be substantially increased at higher power and/or with higher density shelves as is apparent from Figs. 1b and 1c.

To summarize, our results show good absorption by the thermal part of the distribution function which is nearly independent of both polarization and angle, and with Q/nmv_e^3 of typically about 0.1. Finally, we wish to point out that similar results results were found by numerical simulations.[13]

We will now discuss more fully some of the related experimental results. Figure 1e (taken from Ref. 5) shows the reflected light as a function of angle of incidence and polarization, for laser irradiance of 5×10^{15} W/cm^2. Notice that the absorption efficiency is not strongly dependent on either polarization or angle of incidence for tilt angle less than about 60°; just as predicted in Fig. 1d.

We now discuss the relevance of an experiment in which the transport of energy was studied at an irradiance of 10^{15} W/cm^2 through a thin layer of polystyrene into an aluminum substrate.[4] The intensity of aluminum line radiation is shown as a function of polystyrene thickness in Fig. 1f. The absorbed energy flux Q is measured. Assuming a particular value for Q/nmv_e^3 then allows one to calculate the average electron energy near the critical surface. Since the laser energy must ultimate heat the electrons in the polystyrene to this energy, one can calculate how much laser energy, at given irradiance, is needed to just burn through a given layer of polystyrene (i.e., to cut off the aluminum line radiation).

A value of Q/nmv_e^3 of about 0.1 is consistent with the upper limit of $Q/nmv_e^3 \sim 0.2$ inferred from the dependence of Al x-ray radiation to polystyrene thickness shown in Fig. 1f.[4]

The experimental situation is closely one dimensional. The asymmetry of specularly reflected light indicates that, on the average, the center of the critical surface bulges by only about 1 μ compared to the half energy content focal diameter of 30 μ. However, Fourier analysis of the specularly reflected light does show enhanced density fluctuations near 1 μ,[7] which is close to the peak ion fluctuation wavelength.

Finally, we would like to make a few remarks on hard x-ray data. Our own[14] and other theories[8] have shown that resonant absorption creates electron

distributions having non thermal tails extending from about $3v_e$ to 6 or $7v_e$. If 10^{15} W/cm^2 is conducted by the electrons and $Q/nmv_e^3 \sim 0.2$ as indicated in Ref. 4, then the thermal energy is about 6 keV. Thus the non thermal tail would extend from about 60 keV to about 300 keV. The layered target experiments and others[6] show very few hard x-rays above 100 keV. Thus there appears to be no indication of a strong superthermal tail to the electron distribution function.

In summary then, there are good theoretical and experimental indications that light absorption by enhanced ion density fluctuations is a very important process for laser fusion.

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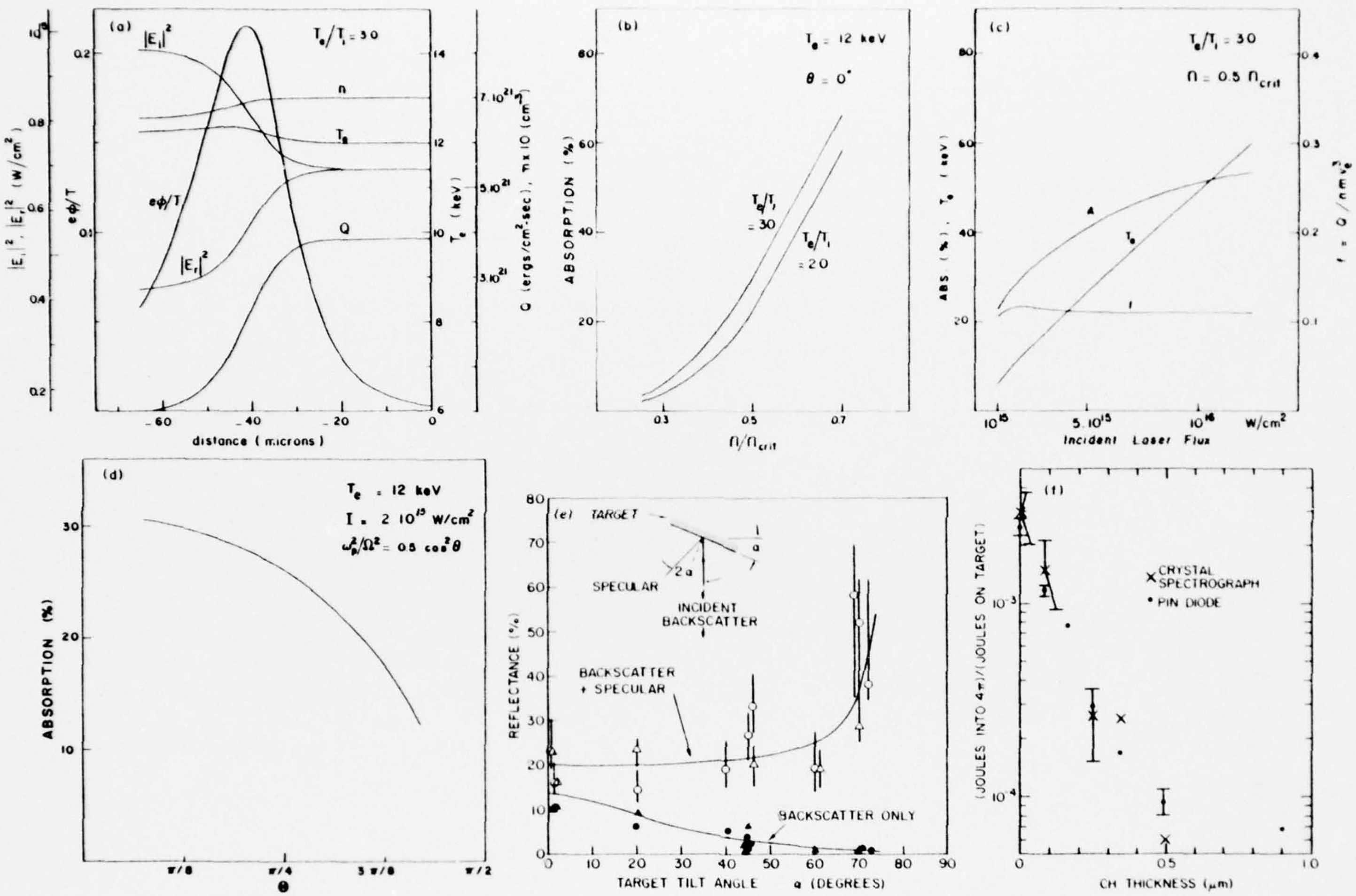

Fig. 1 — (a) Fluid quantities as a function of x, (b) fractional absorption as function of density, (c) fractional absorption, T_e and f as a function of laser flux, (d) fractional absorption as a function of tilt angle, (e) total reflected and backscattered energy as a function of the angle of incidence. Circles and triangles are for the two incident polarizations, and (f) Al-line radiation (X) and continuum (·) (1-3 keV) versus polystyrene thickness.

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